Current status and future of EUV and BEUV source.

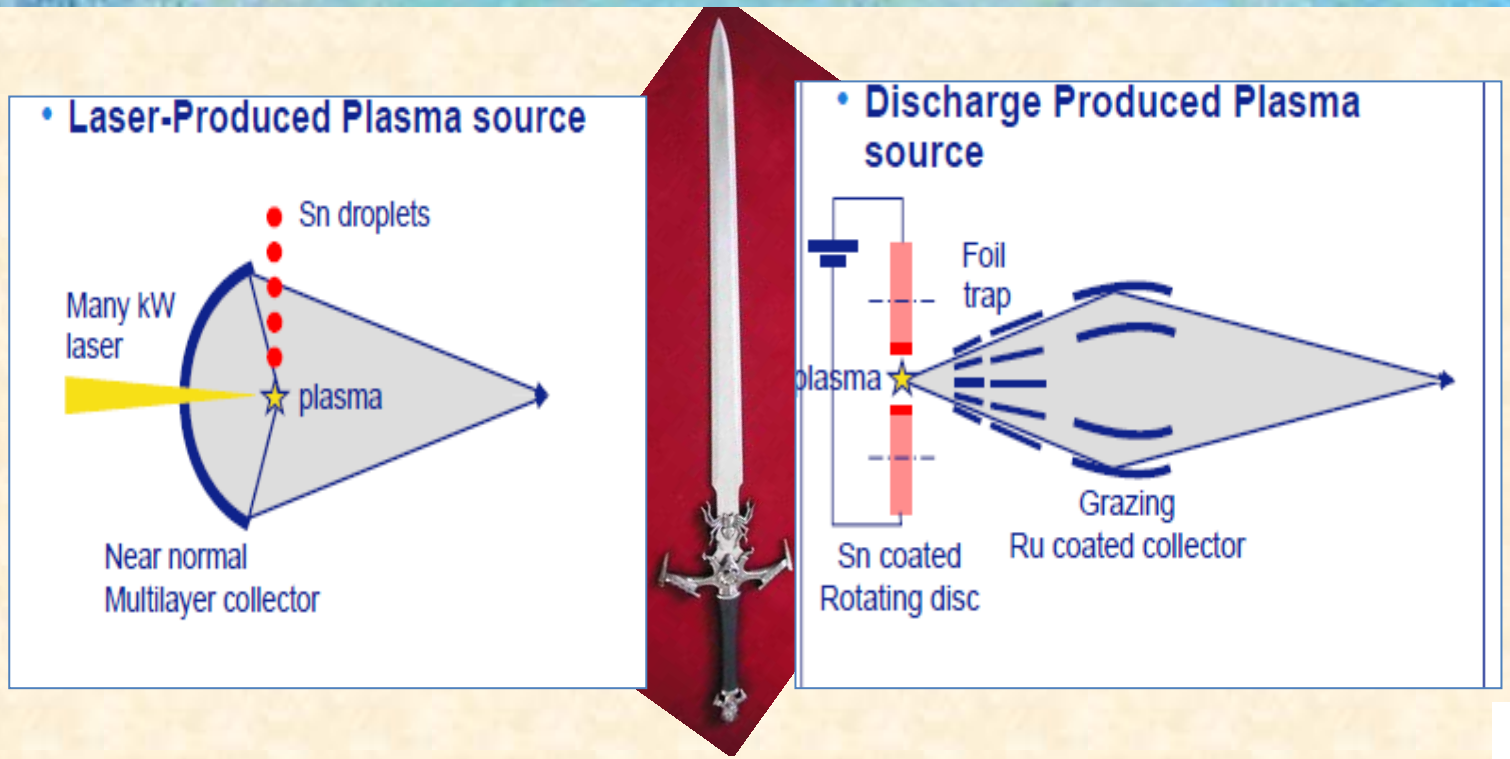
Do we know how to build HVM EUV source?

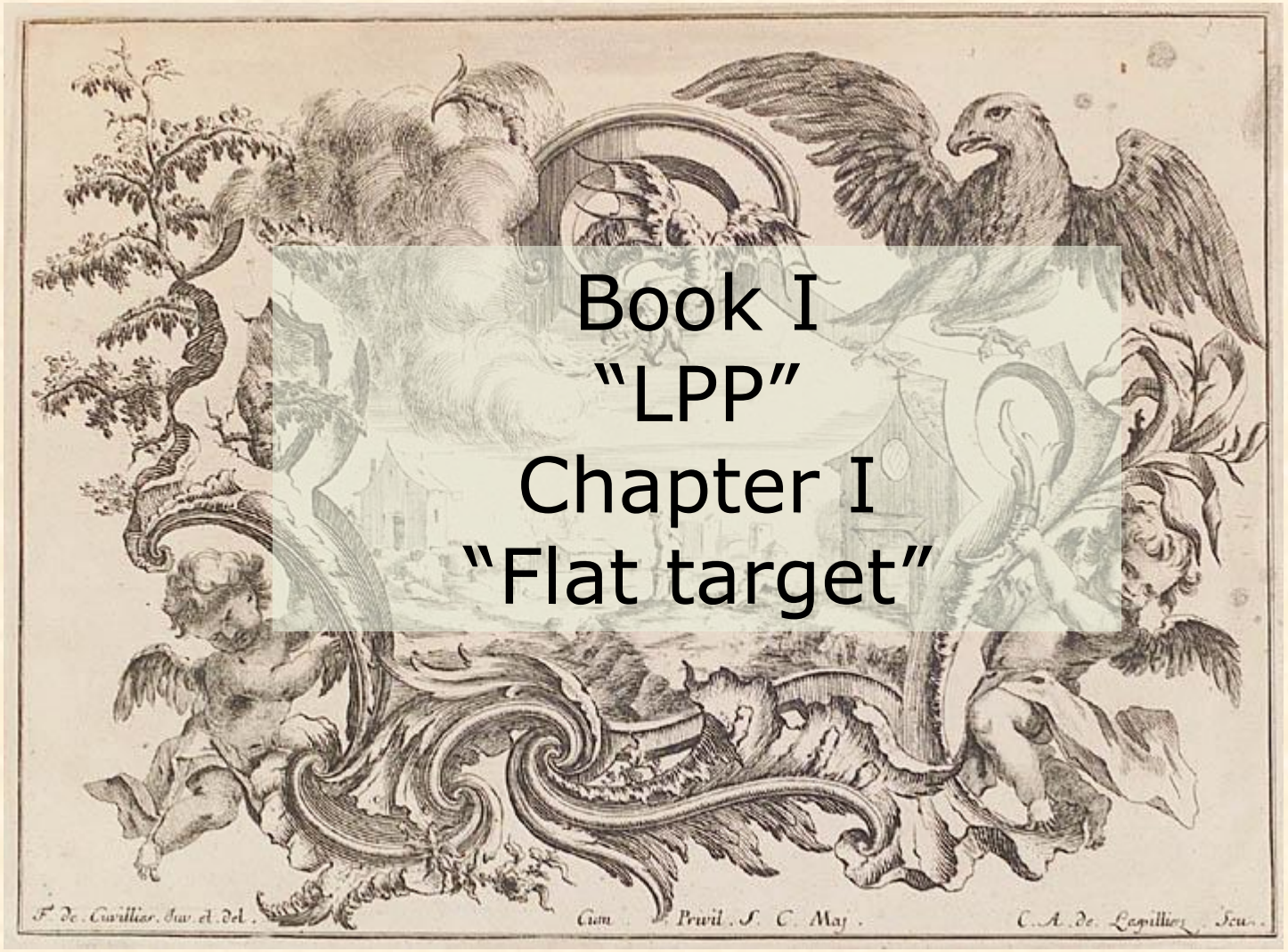
Konstantin Koshelev



www.rnd-isan.ru

Encyclopedia of the Wars of the Roses




Book I
"LPP"
Chapter I
"Flat target"

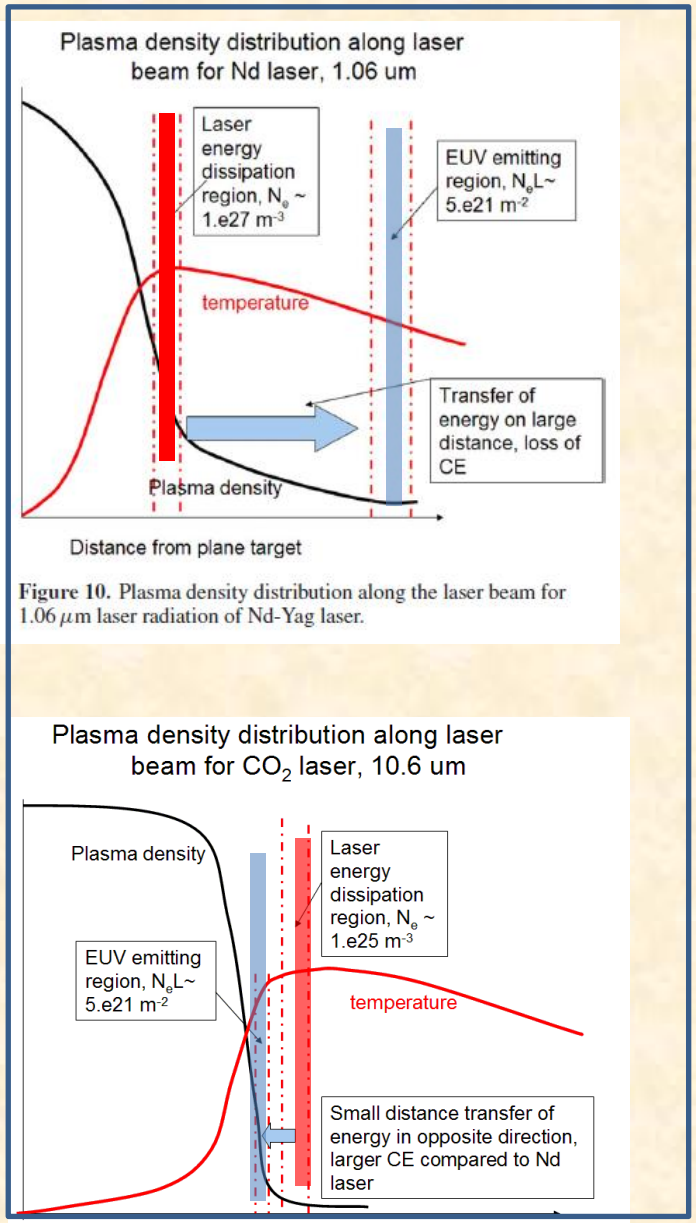


Figure 10. Plasma density distribution along the laser beam for 1.06 μm laser radiation of Nd-Yag laser.

Schematic model of transformation of laser energy to EUV radiation Initial phase:

Absorbed part of laser energy heats and evaporates surface layer of target

Optical breakdown occurs in the evaporated target. Laser power is supposed to be high enough (>~1.e13 W/m^2) for this process

Plasma density increases. This leads to an increased absorption of laser radiation

At plasma density higher than the critical the laser beam does not reach the surface of the plane target anymore.

Schematic model of transformation of laser energy to EUV radiation

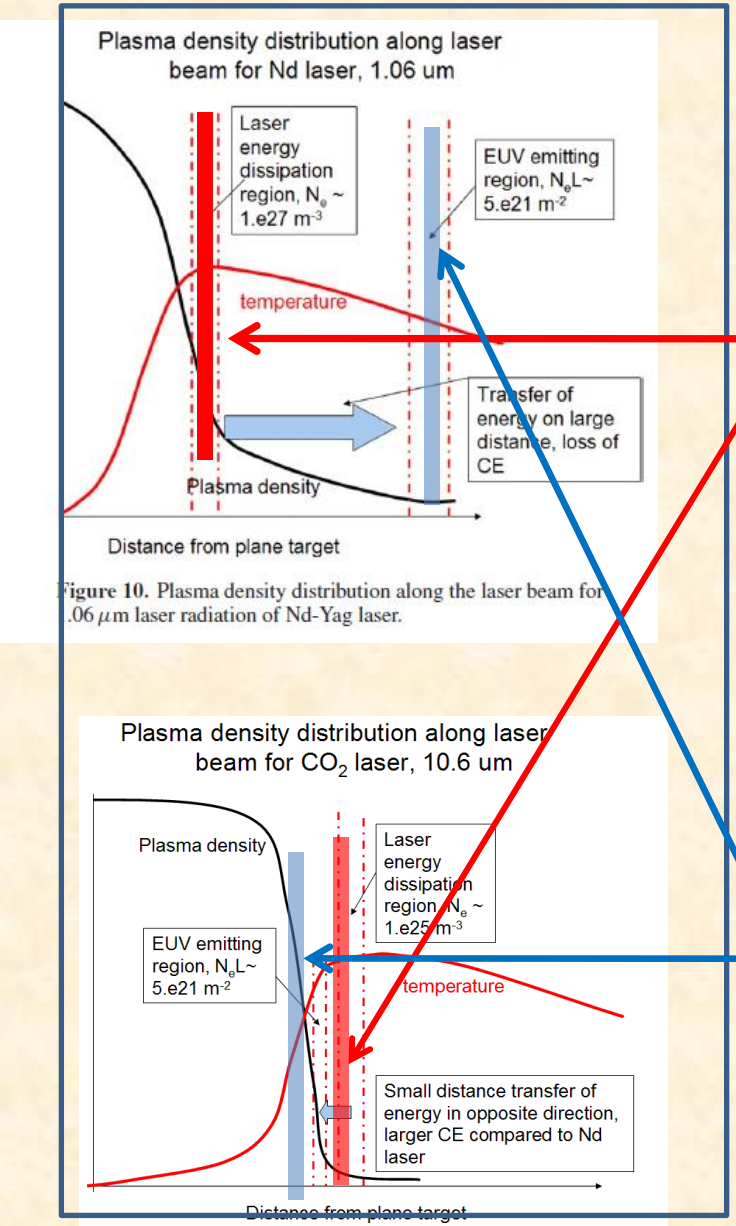


Figure 10. Plasma density distribution along the laser beam for .06 μm laser radiation of Nd-Yag laser.

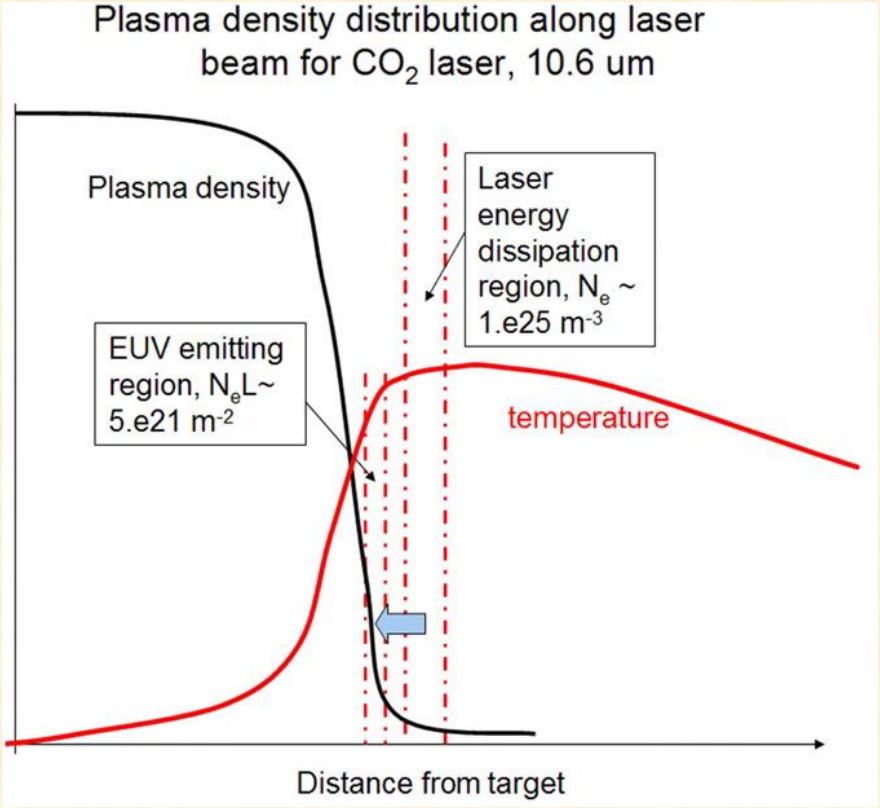
Absorption of laser energy takes place near critical density (1e27 m^{-3} for Nd laser and 1e25 m^{-3} for CO2 laser)

Formation of a plasma region with the high plasma temperature. By a proper choice of laser power density it is possible to "tune" plasma in such a way that it will consist of ions with optimal charge (Sn^{+10} – Sn^{+12}) for radiation around 13,5 nm.

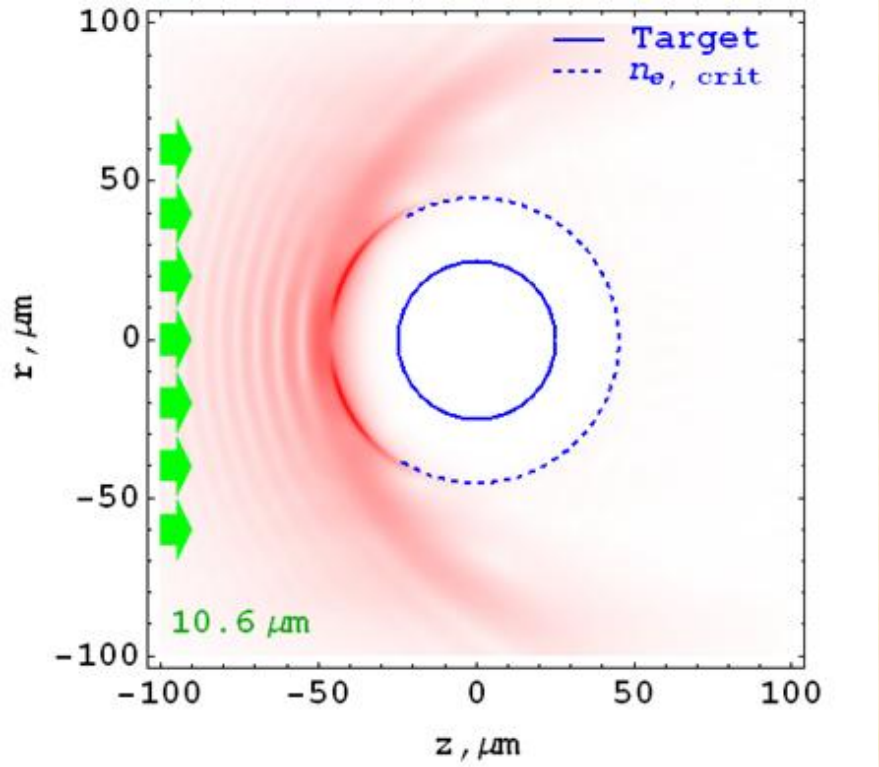
EUV photons can leave the plasma only if they are produced in the region with low optical density - $N_eL \approx 5e21\ m^{-2}$ (shown blue)

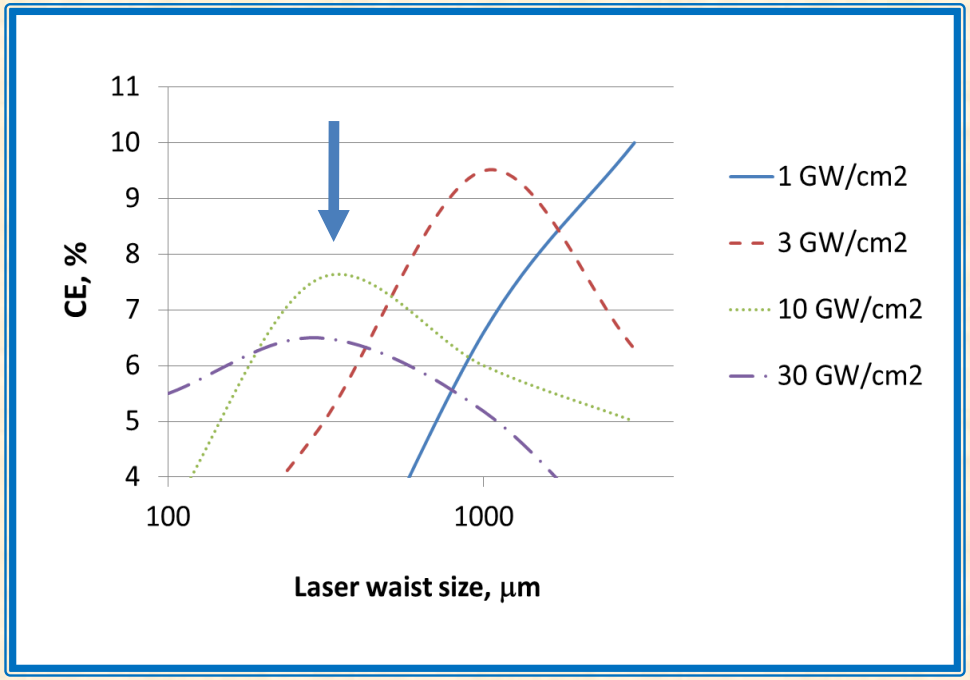
Efficiency of this energy transfer essentially determines an efficiency of conversion of laser energy to "in band" EUV radiation (CE).

Spatial profile of absorption of CO_2 laser radiation



Calculated spatial distribution of 10.6 μm absorption using FDTD solution of Maxwell equations





CE depends on two factors:
Power density and Focus spot size

Calculation made for flat target, CO_2 laser (10,6 μm) and long pulse.

RZLINE + THERMOS-BEELINE

RZLINE - THERMOS_BELINE (R-T-B) modeling complex

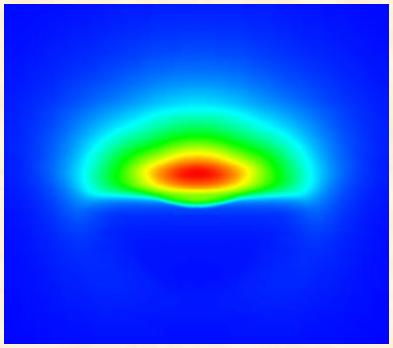
RZLINE code

2D Eulerian RMHD code

Energy fluxes to and from droplet,
absorption and reflection of laser pulse,
electron and ion thermo-conductivity,
radiative transfer in ~100 spectral groups,
evaporation and condensation of target,
ionization and recombination of plasma.

Diffusion-like spectral radiation transport:
calculation of EUV source size,
detailed spectra,
anisotropy of EUV radiation.

Non-homogeneous grid ~ 10^5 r,z cells
Calculation time ~ 2 hours on PC 2.1 GHz



RZLINE works with two types of tables:

1. Transparent case table
2. Optically thick case table (non transparent in band)

Temperature 1 – 500 eV
Electron density 10^{14} – 10^{23} 1/cm^3
Photon energy range 1 – 1000 eV

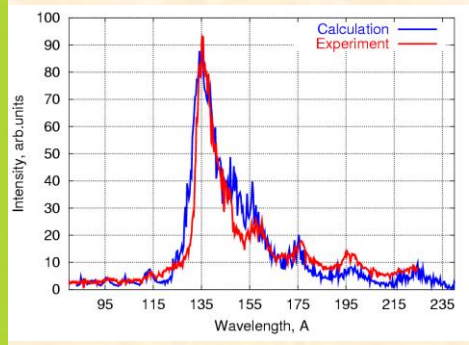
RZLINE - THERMOS_BELINE (R-T-B)

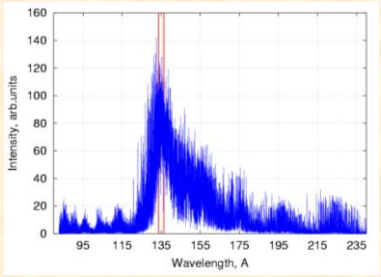
THERMOS_BELINE code:
COMPUTING OF LEVEL KINETICS & RADIATION TRANSPORT

- **Main purpose:**
- **to get CRE tables with arbitrary radiation field;**
- **obtaining the realistic emission spectra;**
- **in-line version for radiative hydro-dynamics;**

Methods:

- **special averaging with given photon energy grid;**
- **using the stored data prepared beforehand.**





The code makes possible self-consistent calculation of level kinetics and radiation transport for arbitrary plasma configurations.

The code includes:

radiation transport of overlapped spectral lines with arbitrary optical thickness and realistic line profiles; verified atomic database for low-Z materials (H, He, C, O) and also for Xe, Sn, W, Tb, Gd.

Flat target demonstrates high CE

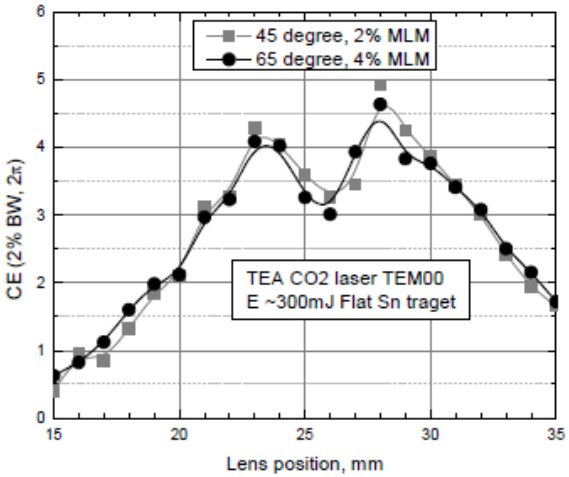


Figure 10. Variation of CE with the focusing lens position in front of flat target.

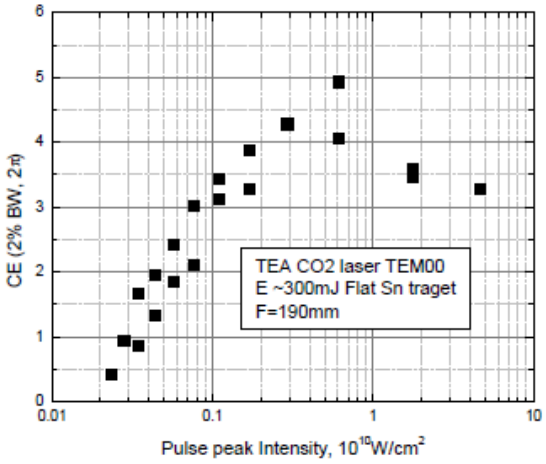


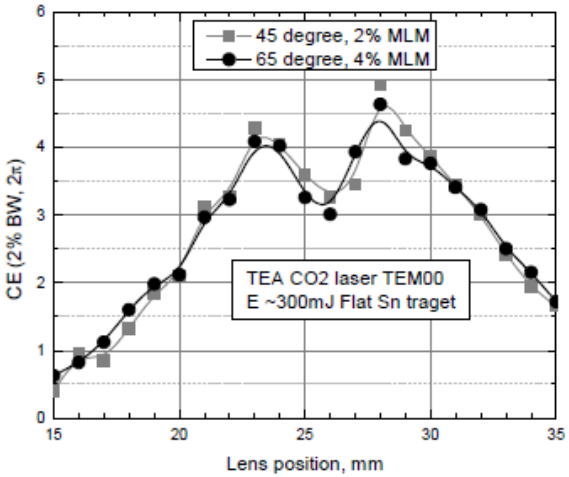
Figure 11. Dependence of CE on pulse peak intensity.

Laser-Produced Plasma Light Source for EUVL

Igor V. Fomenkov*, David C. Brandt, Alexander N. Bykanov, Alex I. Ershov, William N. Partlo, David W. Myers, Norbert R. Böwering, Nigel R. Farrar, Georgiy O. Vaschenko, Oleh V. Khodykin, Jerzy R. Hoffman, Christopher P. Chrobak, Shailendra N. Srivastava, Daniel J. Golich, David A. Vidusek, Silvia De Dea, Richard R. Hou

Proc. of SPIE Vol. 7271 727138-1

Flat target demonstrates high CE



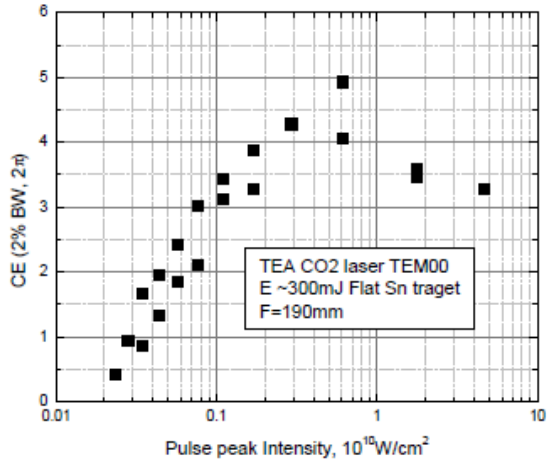
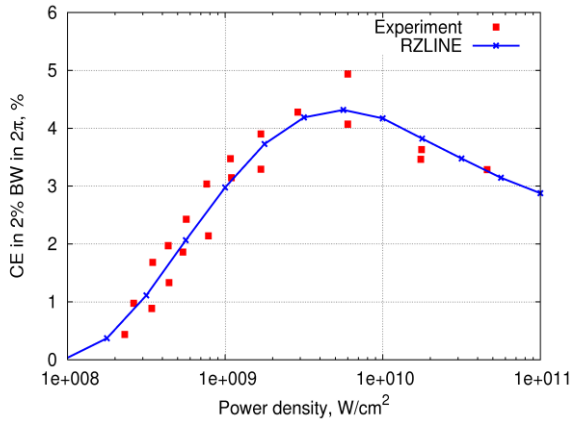


Figure 10. Variation of CE with the focusing lens position in front of flat target.

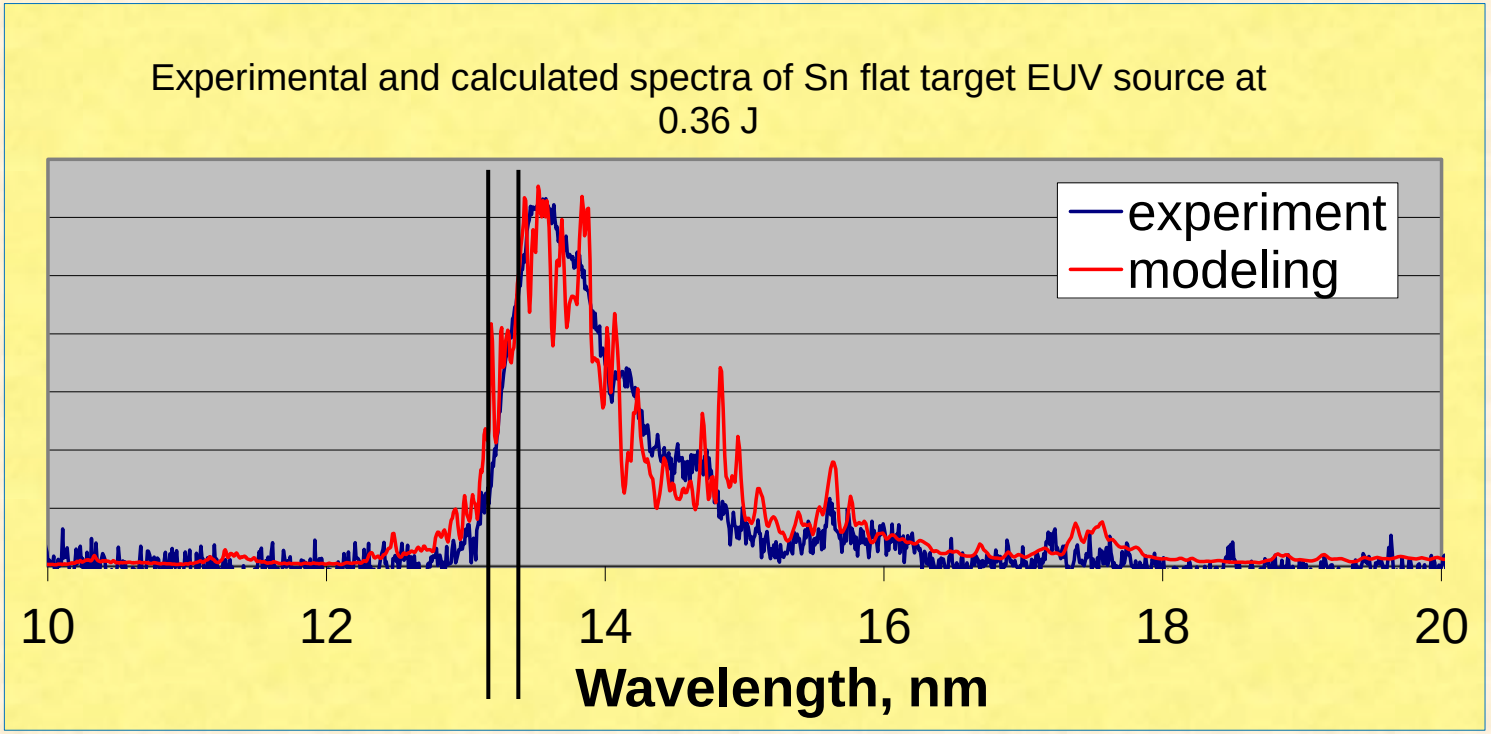


(R-T-B)

There exists an optimal spot size at given laser pulse energy

Laser focus spot

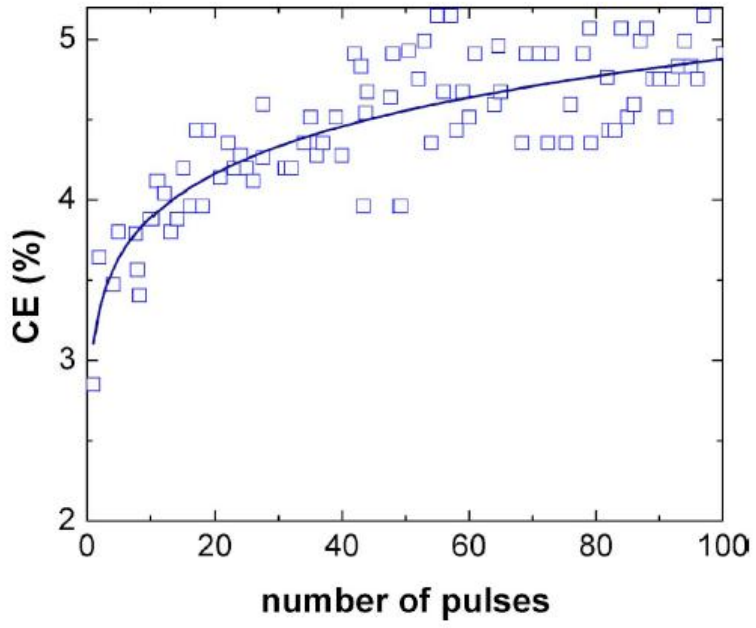
(R-T-B) modeling



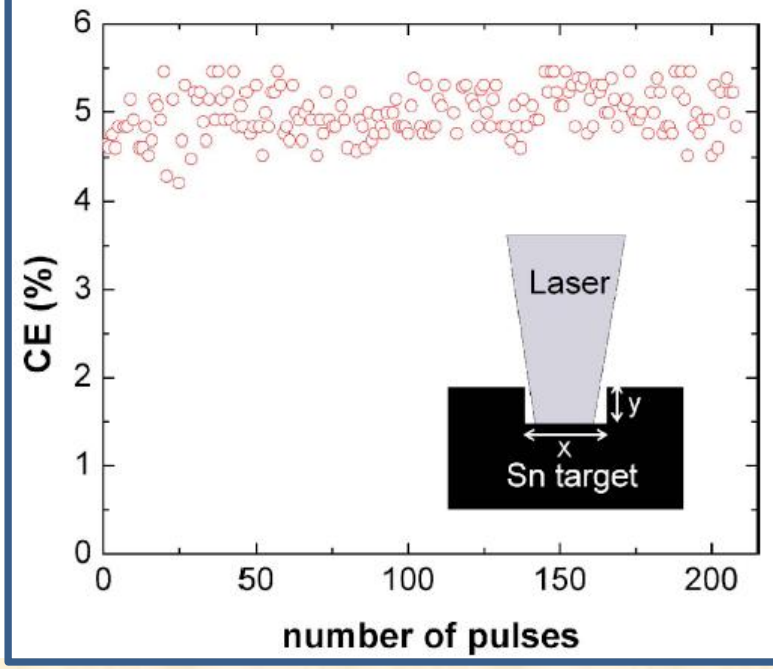
1. **Experimental and calculated spectra coincide rather well**
2. **Other spectral regions were calculated too, though without detailed grid. Only negligible part of energy was emitted there ~< 1%**
3. **Smoothed character of experimental spectra near in-band region is connected with its relatively low resolution.**

"Profiled" targets demonstrate even higher CE

"Digging" a hole in a flat target by repeatedly heating CO2 laser to the same spot



Experiment with the channeled target



Efficient laser-produced plasma extreme ultraviolet sources using grooved Sn targets

S. S. Harilal,[a] T. Sizyuk, V. Sizyuk, and A. Hassanein
School of Nuclear Engineering and Center for Materials Under Extreme Environment, Purdue University, 400 Central Drive, West Lafayette, Indiana 47907, USA

Flat target – pro & contra

POSITIVE	NEGATIVE
•High CE •Comparatively low IR reflection •Possibility for "multiplication" (e.g. by moving target) • Profiled targets shows even higher CE value •…….	•EUV obscuration •Possibly too high amount of evaporated tin •Droplets originated from melted tin surface •…..

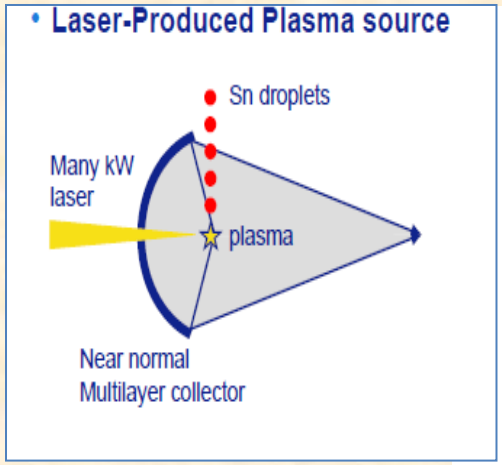
Negative items were found more essential thus possibilities to use flat (modified flat) targets haven't been explored further. This "chapter" was closed.

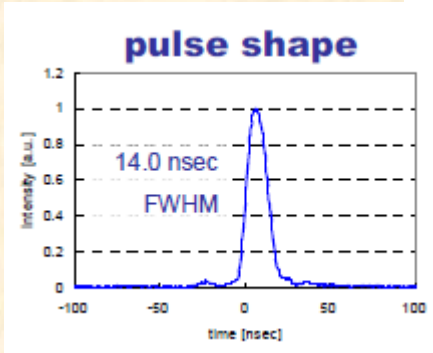
Probably too early !



Chapter II "Mass limited (droplet) targets"

The main price one has to pay for the "mass limited" regime is an essential decrease of CE.





100W 1st Generation Laser-Produced Plasma light source system for HVM EUV lithography

Hakaru Mizoguchi*1, Tamotsu Abe, Yukio Watanabe, Takanobu Ishihara, Takeshi Ohta, Tsukasa Hori, Tatsuya Yanagida, Hitoshi Nagano, Takayuki Yabu, Shinji Nagai, Georg Soumagne, Akihiko Kurosu, Krzysztof M. Nowak, Takashi Suganuma, Masato Moriya, Kouji Kakizaki, Akira Sumitani, Hidenobu Kameda*1, Hiroaki Nakarai*1, Junichi fujimoto *1

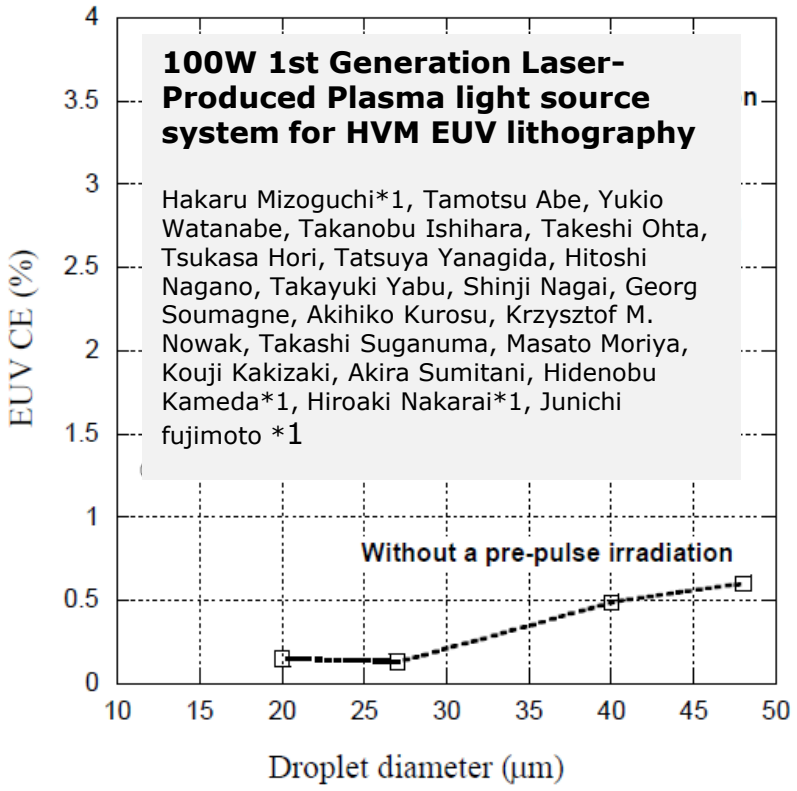
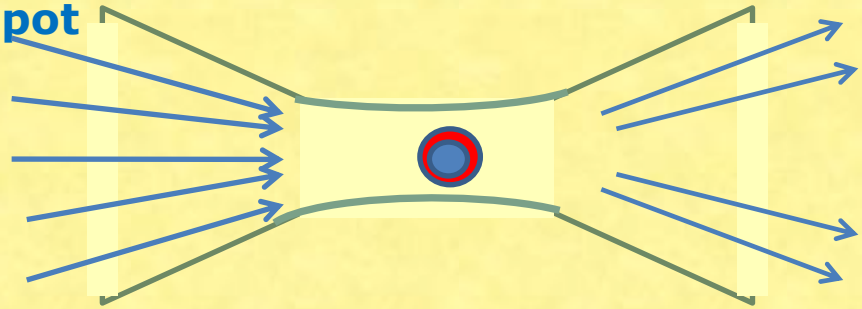


Figure 7. EUV CE as a function of the droplet diameter

Droplet targets - Low CE :

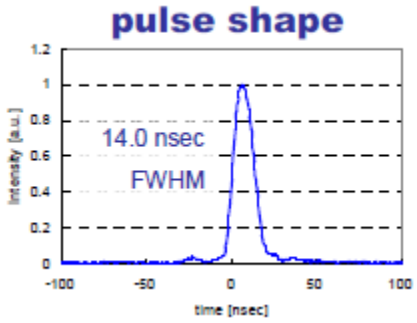
•droplet size is significantly smaller than the laser focusing spot

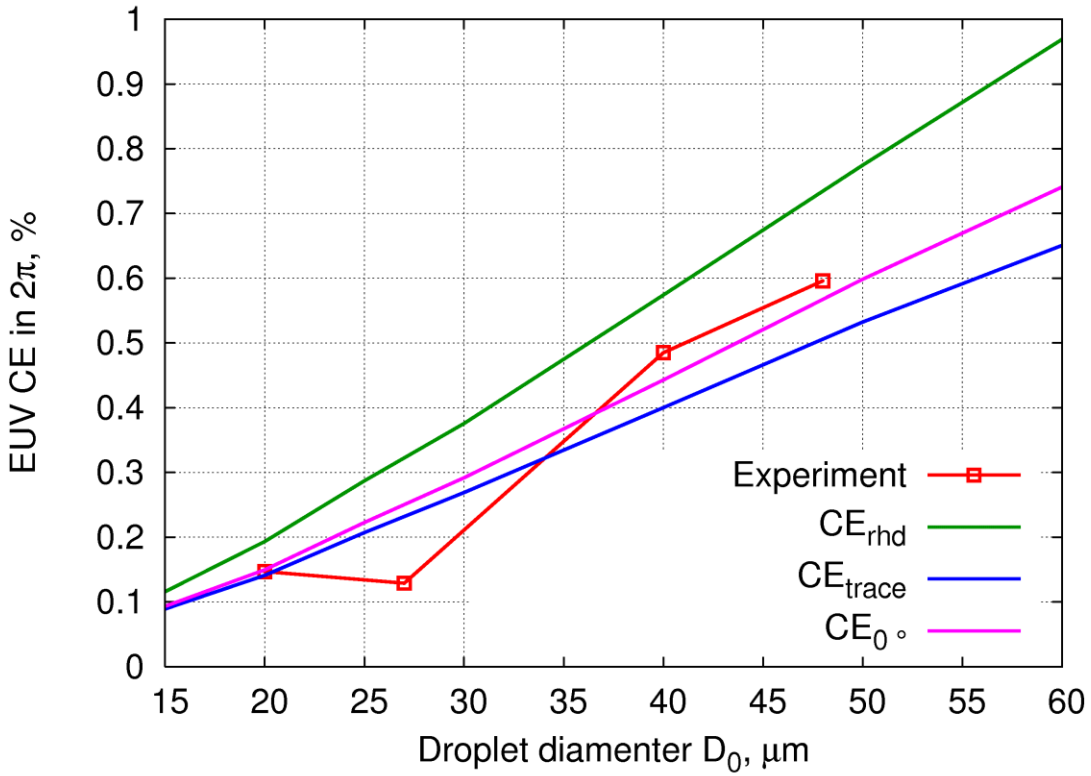


During initial phase of the laser pulse large (or short pulses) an essential part of radiation might pass the droplet without being absorbed.

* Characteristic length of plasma density gradient is proportional to the droplet size and is smaller than that in the plane target regime.
 * The life-time of ions in hot plasma is shorter
 * IR reflection is higher
* Radiation of the droplet plasma is more isotropic and less than half of all originated photons can be collected.

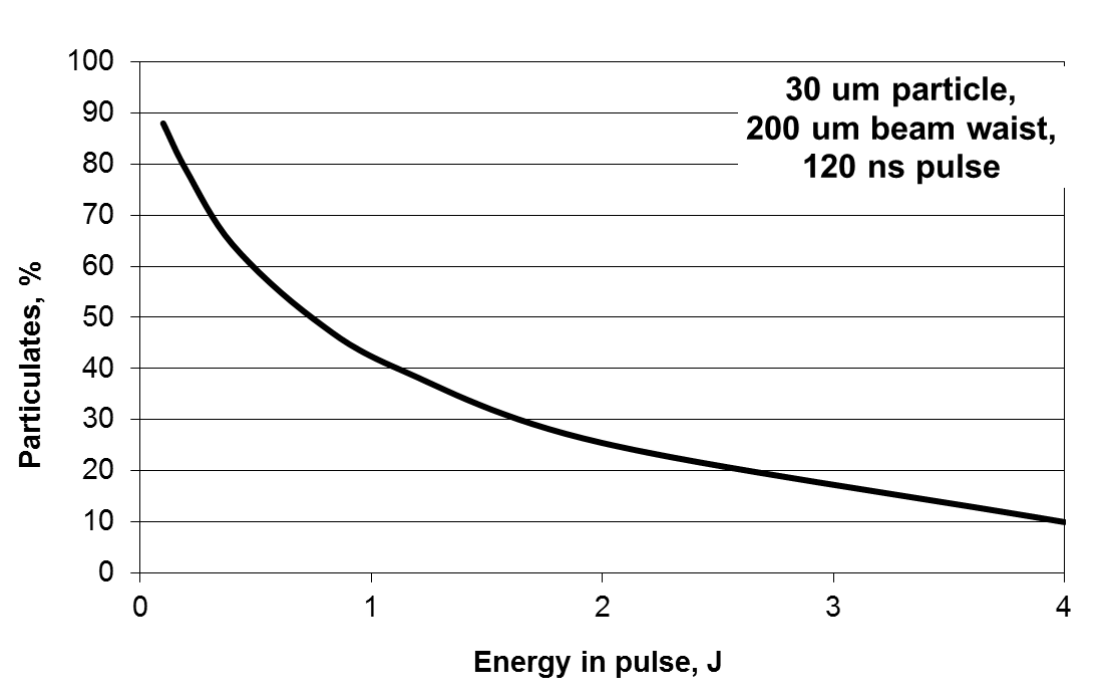
Experimental and theoretical *(R-T-B)* estimates for small (<~30 um) single droplet type targets do not exceed 1 – 2%.





RZLine + THERMOS-BEELINE code

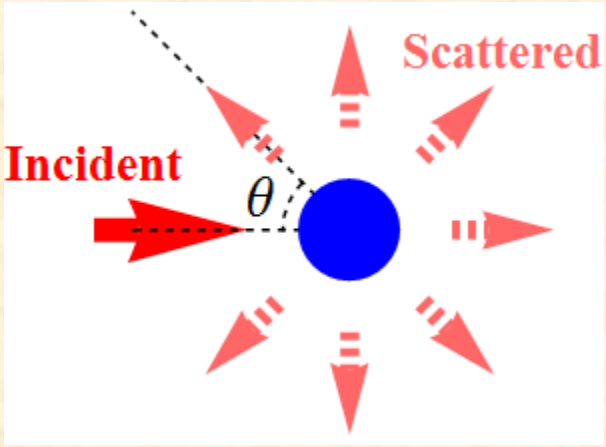
Droplets target are not that "mass limited" as desired



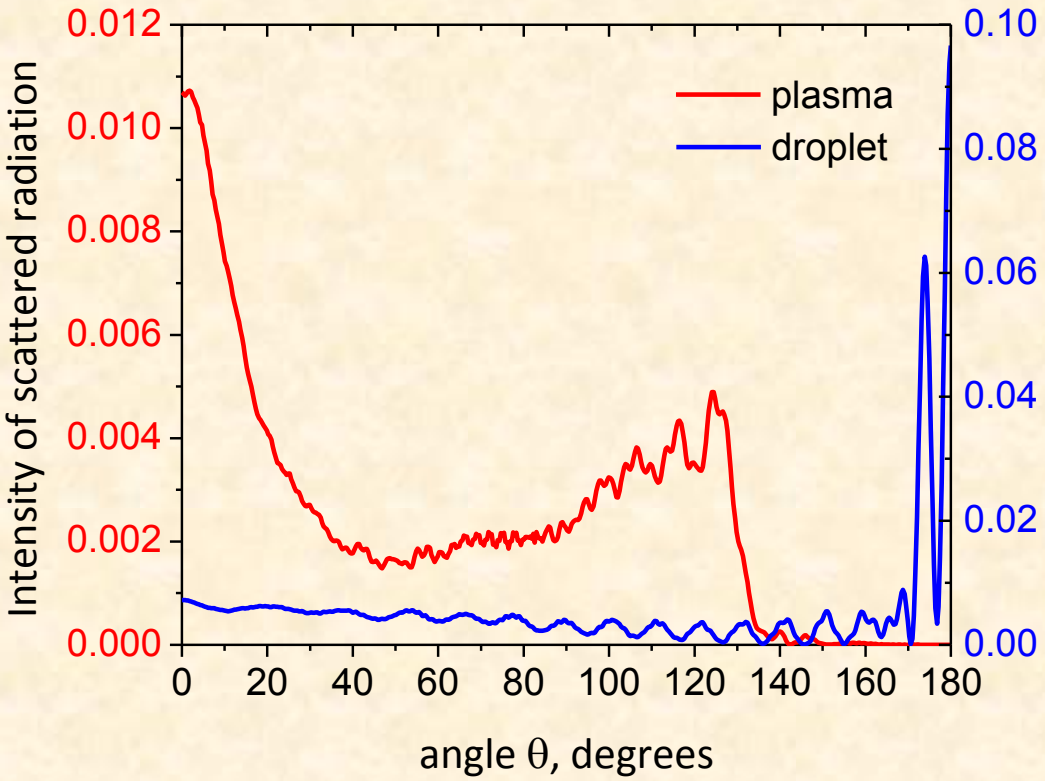
Fraction of droplets which not vaporized after laser pulse even for longer pulses

The modeling has been made for a 30 mm Sn droplet, beam waist at droplet of 200 mm and for pulse duration of 120 ns.

Angular distribution of scattered CO_2 laser radiation



Calculated angular distribution of scattered laser radiation using FDTD solution of Maxwell equations



- **Profile of plasma refractive index is calculated by using plasma parameters (n_e, n_i, T_e, Z) from the RZLINE code (R-T-B) and Drude model**

- **The calculated profile was used for solving of a scattering distribution.**

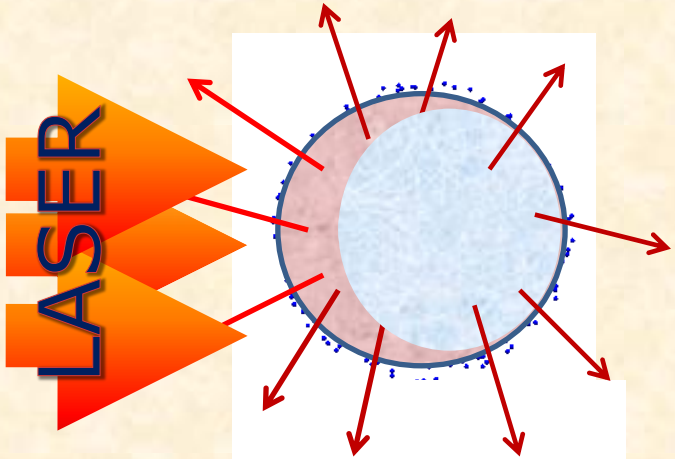
Mass limited – pro & contra

Mass Limited High collectable angle	•Droplets are not fully evaporated • Low CE • High IR reflection due to steep density profile •Necessity for laser-droplet synchronization



Chapter III
Distributed (mist) target

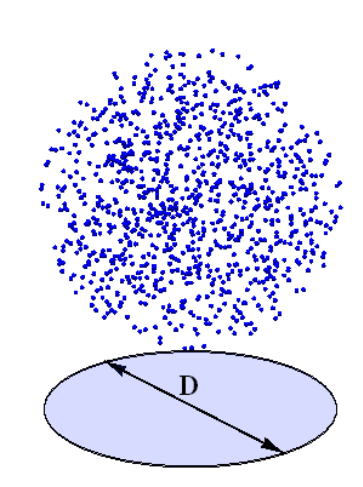
The Ideal Target (I)



- Vapor cloud with a density below "critical" to avoid reflection of a laser radiation
- size of few hundreds um to provide full absorption of laser radiation

Expected high CE Low IR radiation scattering Appropriate source size	• Very short life time (!) – Expansion velocity 5e6 cm/s D = 3e-2 cm Time = few nanoseconds

The Ideal Target (II) – distributed (mist) target.



An example – suspension of microparticles in a water droplet. Two lasers – the first to heat and evaporate water; the second to produce hot radiating plasma.

Consists of a number of fragments with a size > 1 um to provide continuous supply of vapor to the target volume during laser pulse duration.
Lifetime could be adjusted by variation of a total mass and single fragment size.

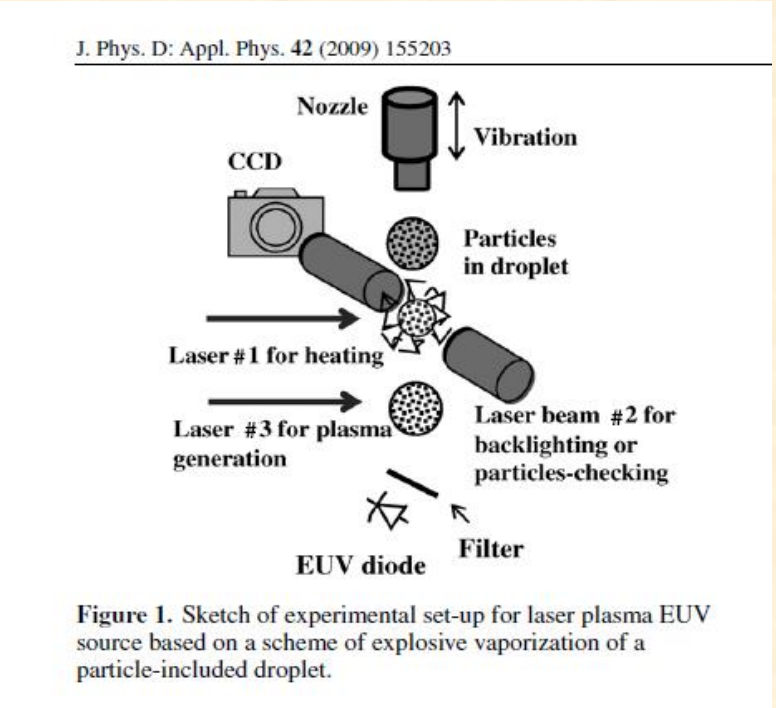


Figure 1. Sketch of experimental set-up for laser plasma EUV source based on a scheme of explosive vaporization of a particle-included droplet.

Jingquan Lin[1,2] and Toshihisa Tomie[2]

100W 1st Generation Laser-Produced Plasma light source system for HVM EUV lithography

Hakaru Mizoguchi*1, Tamotsu Abe, Yukio Watanabe, Takanobu Ishihara, Takeshi Ohta, Tsukasa Hori, Tatsuya Yanagida, Hitoshi Nagano, Takayuki Yabu, Shinji Nagai, Georg Soumagne, Akihiko Kurosu, Krzysztof M. Nowak, Takashi Suganuma, Masato Moriya, Kouji Kakizaki, Akira Sumitani, Hidenobu Kameda*1, Hiroaki Nakarai*1, Junichi fujimoto *1

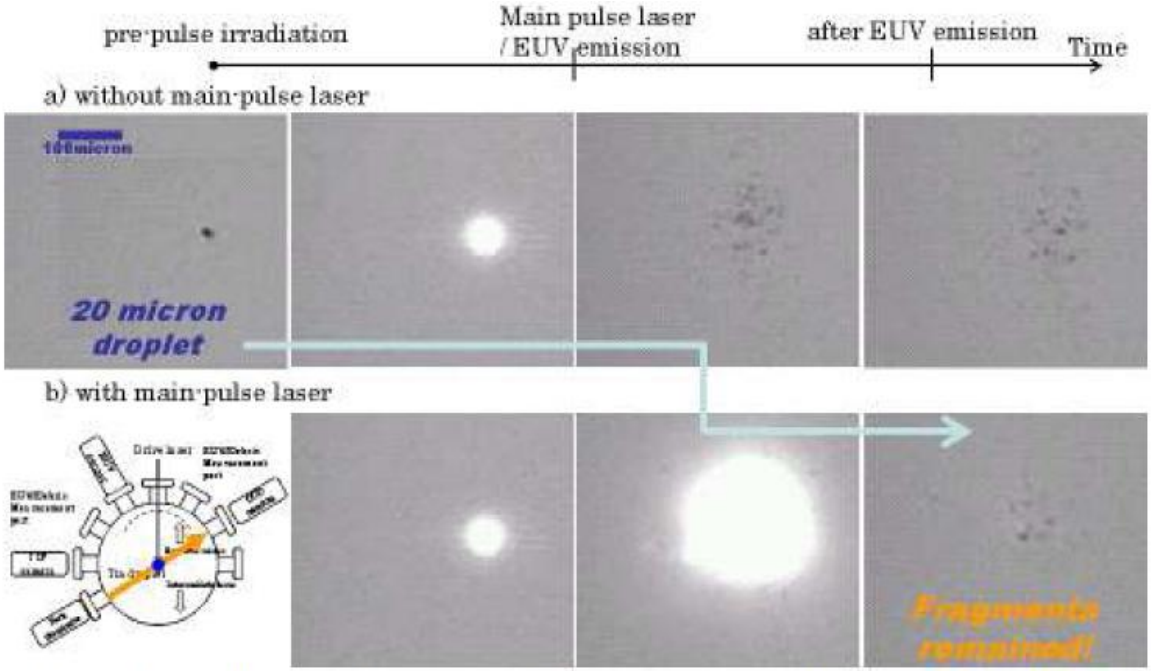


Figure 5. Shadowgraph images of the Sn fragments I (a proper condition)

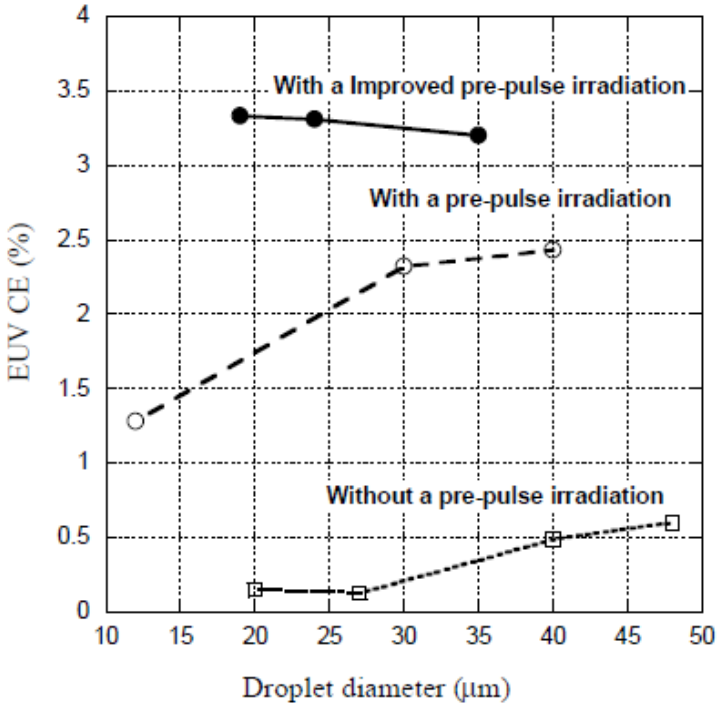
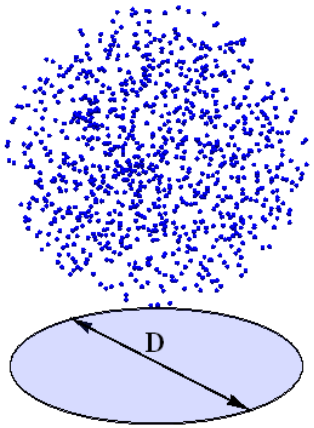


Figure 7. EUV CE as a function of the droplet diameter

CE vs mist expansion dimension (R-T-B)

Mist target parameters:

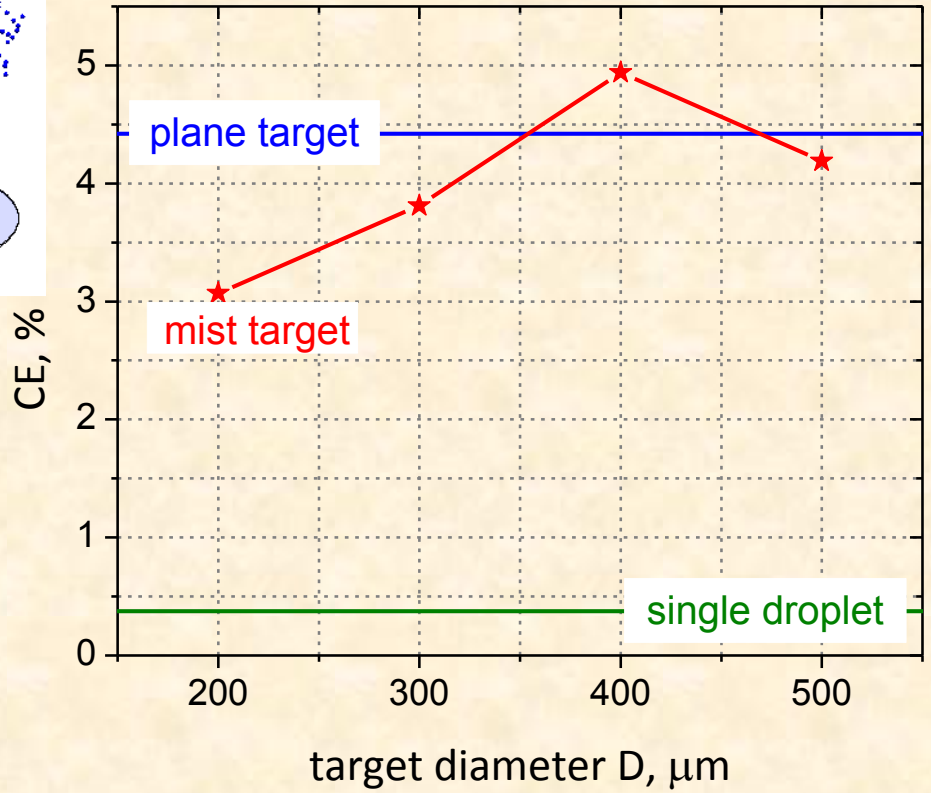
- 30 um droplet expanded spherically
- uniformly spread fragments
- fragment size 1 μm



Laser pulse parameters:

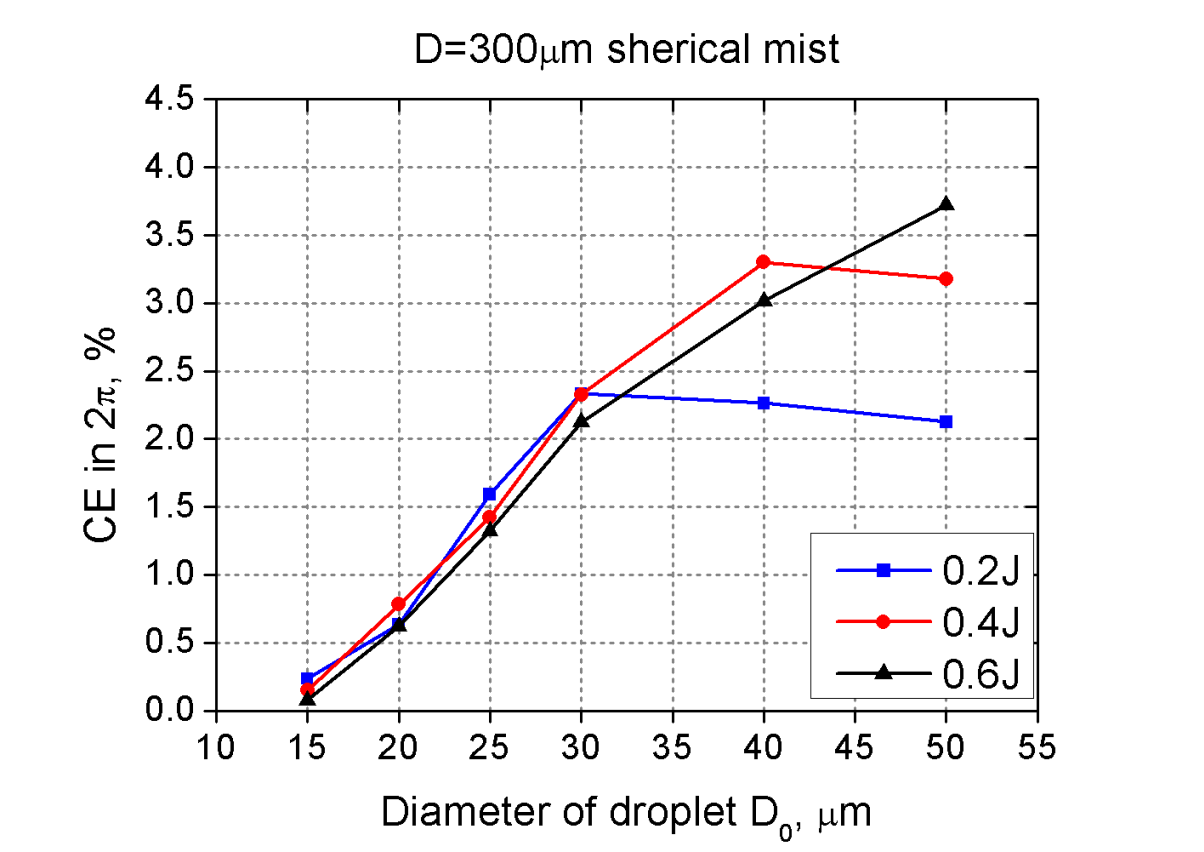
- Gaussian time shape
 - 15ns FWHM
- Gaussian intensity profile in focal spot
 - 300 μm diameter on $1/e^2$ intensity level
- pulse energy – 0.1J
 - ~10^{10} W/cm^2 power density

RZLINE calculations: in-band CE in 2π



CE calculated with account for EUV angular anisotropy

300 um mist target CE vs laser initial droplet size (R-T-B)



APPLIED PHYSICS LETTERS 92, 241502 (2008)

Pure-tin microdroplets irradiated with double laser pulses for efficient and minimum-mass extreme-ultraviolet light source production

Shinsuke Fujioka,[1,a)] Masashi Shimomura,[1] Yoshinori Shimada,[2] Shinsuke Maeda,[1] Hirokazu Sakaguchi,[1] Yuki Nakai,[1] Tatsuya Aota,[1] Hiroaki Nishimura,[1] Norimasa Ozaki,[3] Atsushi Sunahara,[2] Katsunobu Nishihara,[1] Noriaki Miyanaga,[1] Yasukazu Izawa,[1] and Kunioki Mima[1]

[1]*Institute of Laser Engineering, Osaka University, 2-6 Yamada-Oka, Suita, Osaka, 565-0871 Japan*
[2]*Institute for Laser Technology, 2-6 Yamada-Oka, Suita, Osaka, 565-0871 Japan*
[3]*Graduate School of Engineering, Osaka University, Suita, Osaka, 565-0871 Japan*

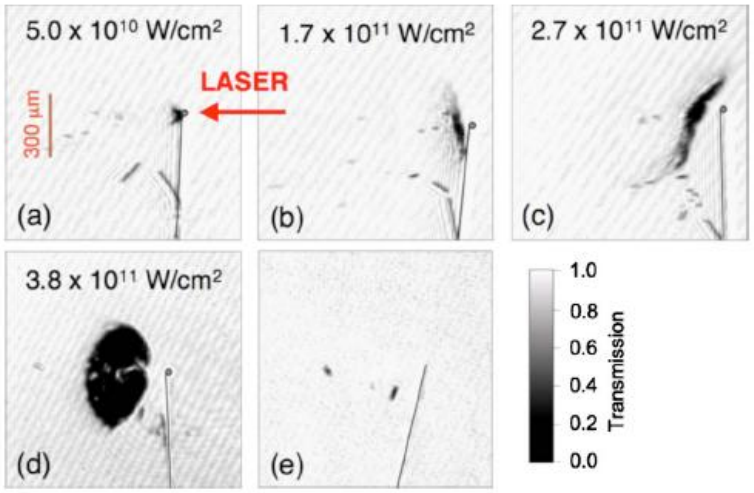


FIG. 1. (Color online) Side-on shadowgraphs of expanded microdroplets were taken 0.5 μs after the laser irradiation. The artificial shadows indicate the initial position and shape of the droplet. Laser intensities were, respectively, (a) 5.0×10^{10}, (b) 1.7×10^{11}, (c) 2.7×10^{11}, and (d) 3.8×10^{11} W/cm^2. (e) No expansion was observed when only a carbon fiber was irradiated with a prepulse. The expansion of the laser-irradiated microdroplets changed drastically when the laser intensity was increased.

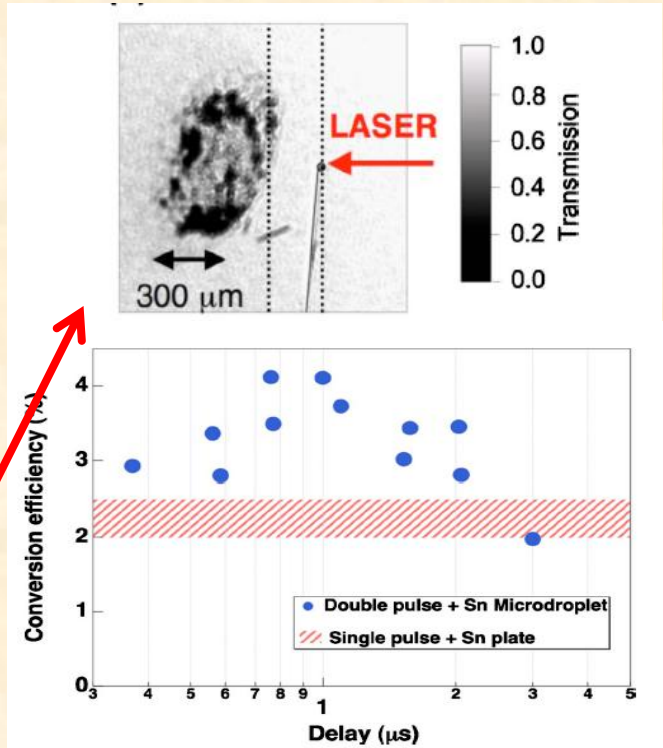
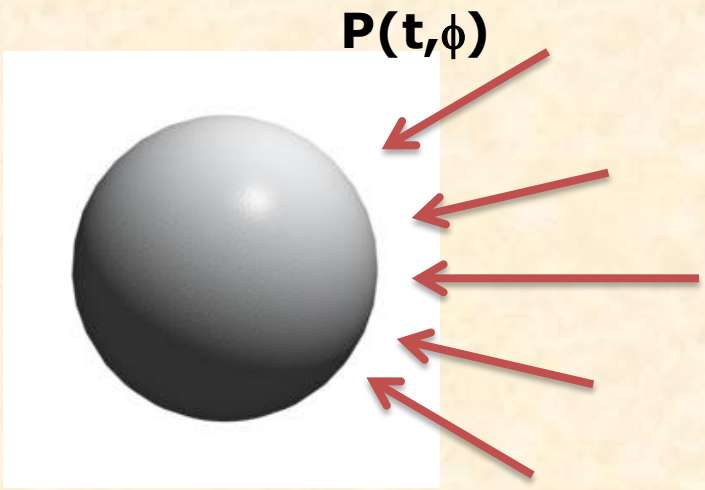


FIG. 2. (Color online) Energy conversion efficiencies of the main CO_2 laser beam to 13.5 nm wavelength light within a 2% bandwidth. The conversion efficiencies were measured by varying the temporal separation between the main CO_2 pulse and the Nd:YAG prepulse. An EUV-CE of 4% was attained by this scheme.

Modeling of splitting tin drops under the action of laser radiation.

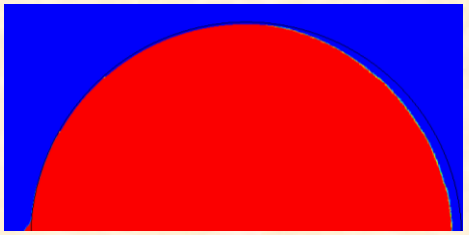
1 stage. Calculation of droplet acceleration under laser pulse load



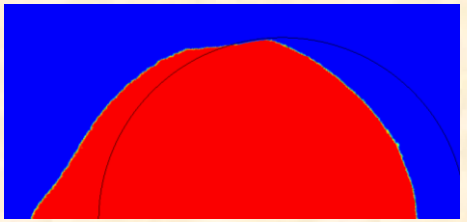
Axi-symmetric pressure distribution is applied at the droplet surface

Droplet shape after laser inpact

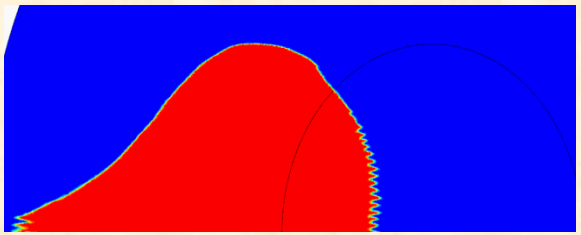
Weak (V_{max}= 100 m/s)



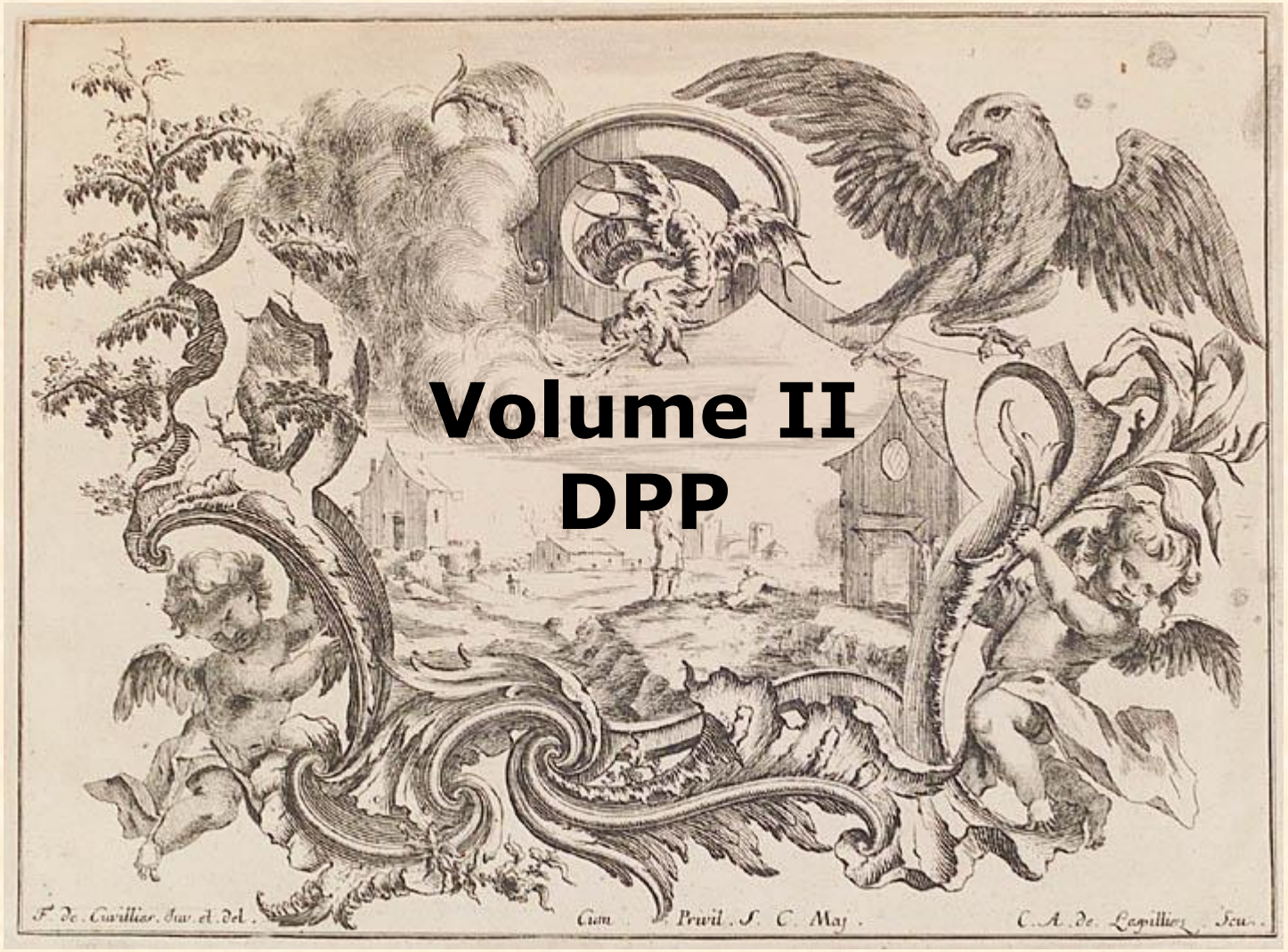
Medium (V_{max}= 300 m/s)



Strong (V_{max}= 800 m/s)



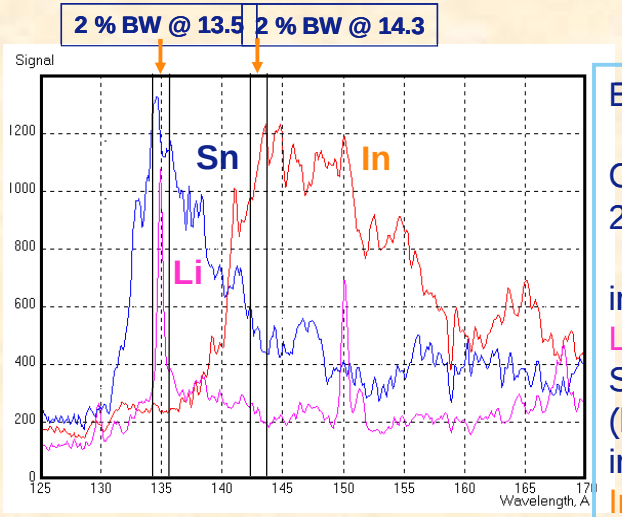
Initial droplet position is shown by black line


Volume II
DPP

Long prehistory

Li, Xe • • •

Vacuum spark (ASML-ISAN) 2000

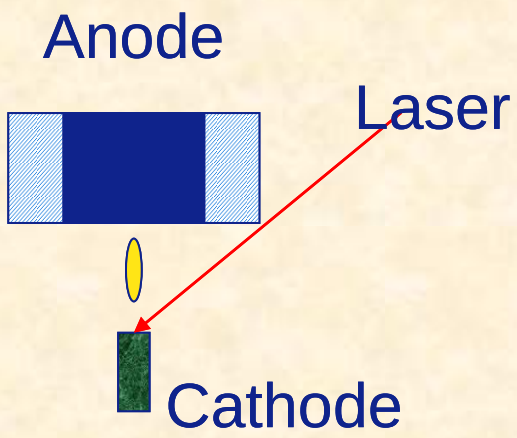


E_{in}= 3 J

CE (2% BW, 2π):

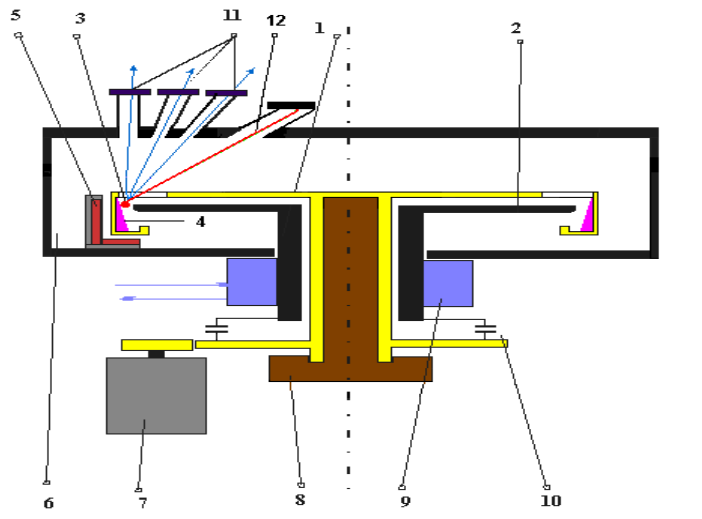
in 13.5nm:
Li = 0.5%
Sn = 2 - 3.5 % (best ever)
in 14.3 nm:
In = 1 %

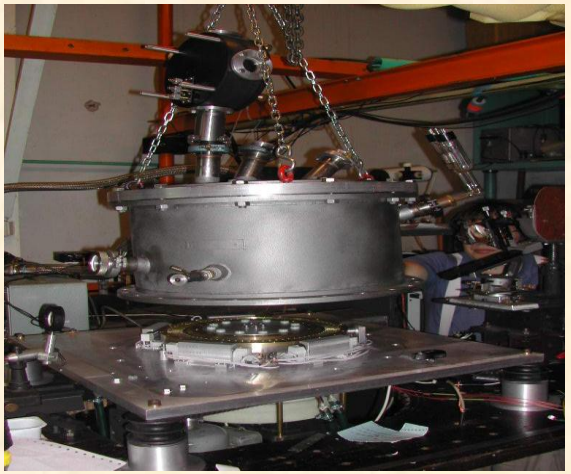
Concern: Potentially increased debris production with respect to gaseous materials



The first usage of Sn as EUV source fuel

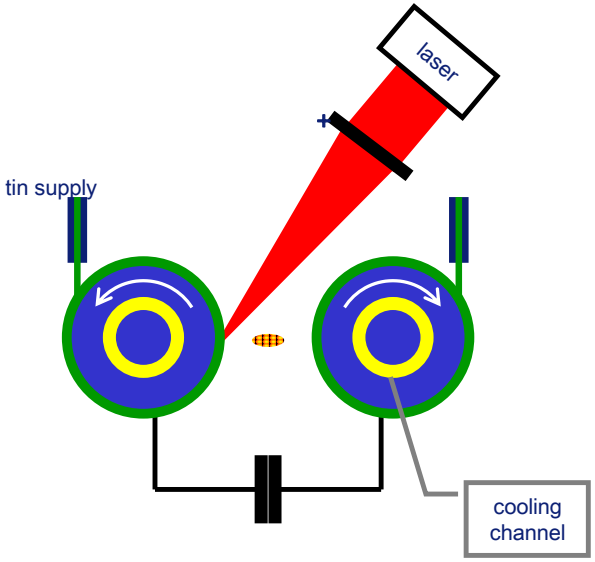
Rotating disks multiplexing 2001 (ISAN-ASML)





Modified source variant is still operating in RnD ISAN with cruise power up to 20 kW.

Philips‘ EUV Lamp: Sn-based rotating electrodes

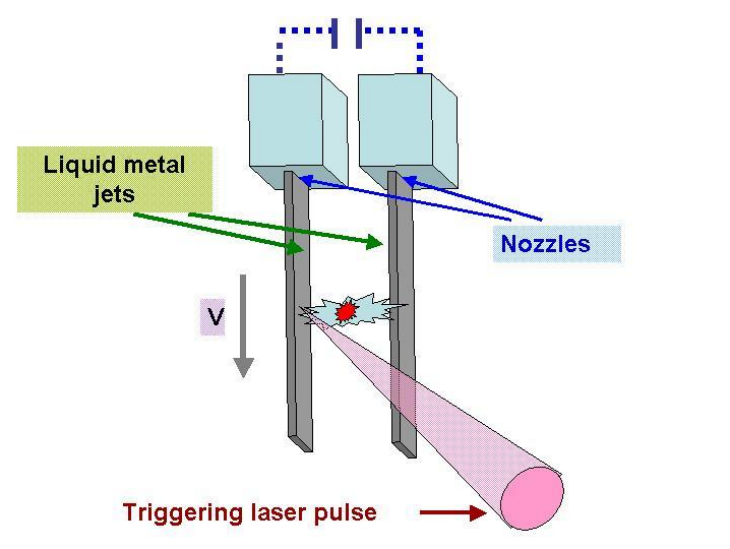




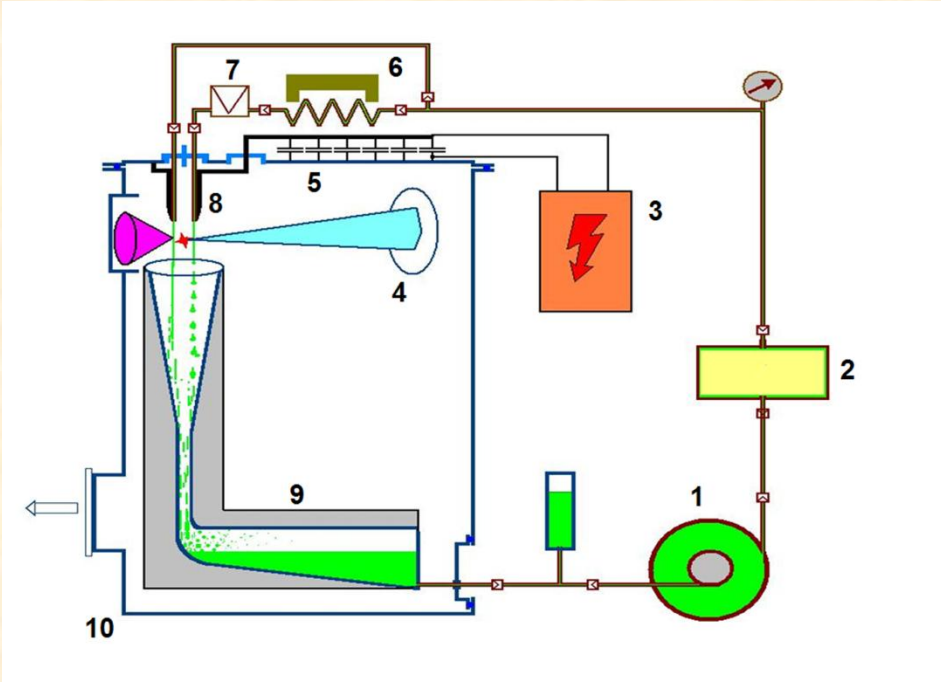
- 200W/2π continuous operation (scalable to >600W /2π)
- very small pinch (<1mm)
- >>1 bln shots electrode life
- commercial product

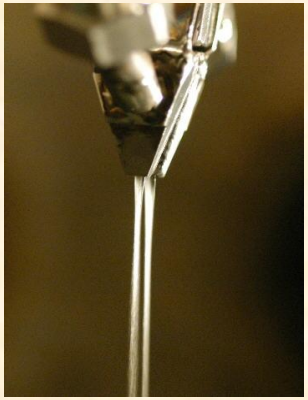
Philips Extreme UV

Liquid tin jet electrodes discharge



New approach to multiplication of DPP source was proposed in 2006 in frame of MoreMoore Project.





Jet – Proto I (2005 – 2007)



Principal Characteristics :

Capacitor - 0,4 uF
Inductance – 12 – 15 nH
Stored energy – up to 5 J

Cruise – 4 kHz x 2,5 J = 10 kW
Burst - 4 kHz x 5 J = 20 kW – (20 s) – water cooling limitation

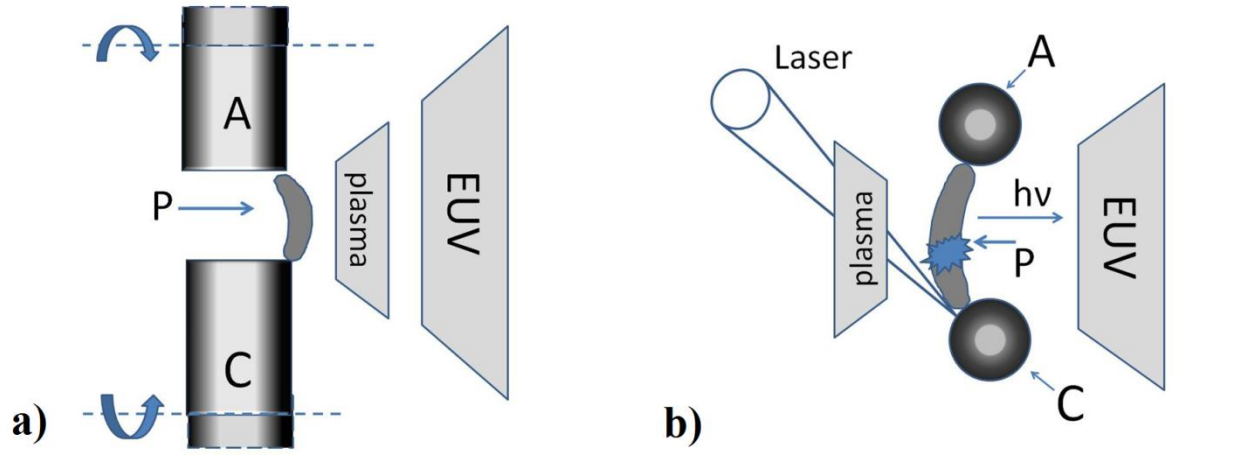
Jet material – Sn (8,5%) : Ga eutectic alloy (30 °C)

Jet velocity – 10 m/s
CE = 1,3 % (corresponds to alloy composition)

Demonstrated advantages of new approach:

- Technically more simple and reliable system (No moving part except liquid tin jets)
- Open system - High collectable angle
- In built debris mitigation features
- Free orientation in space
- High speed of electrode material renewal (up to 30 m/sec) allows operation at higher heat load

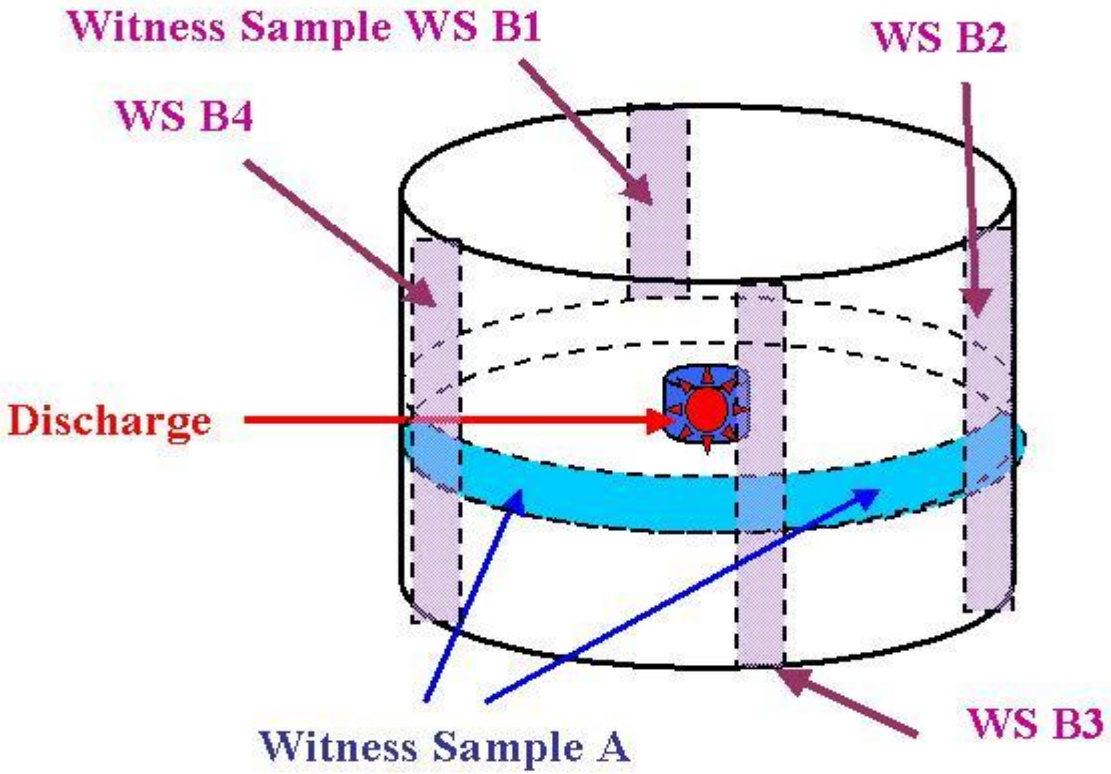
In-built debris mitigation features – Direction of plasma debris lays outside EUV collectable angle



Conventional wheel geometry

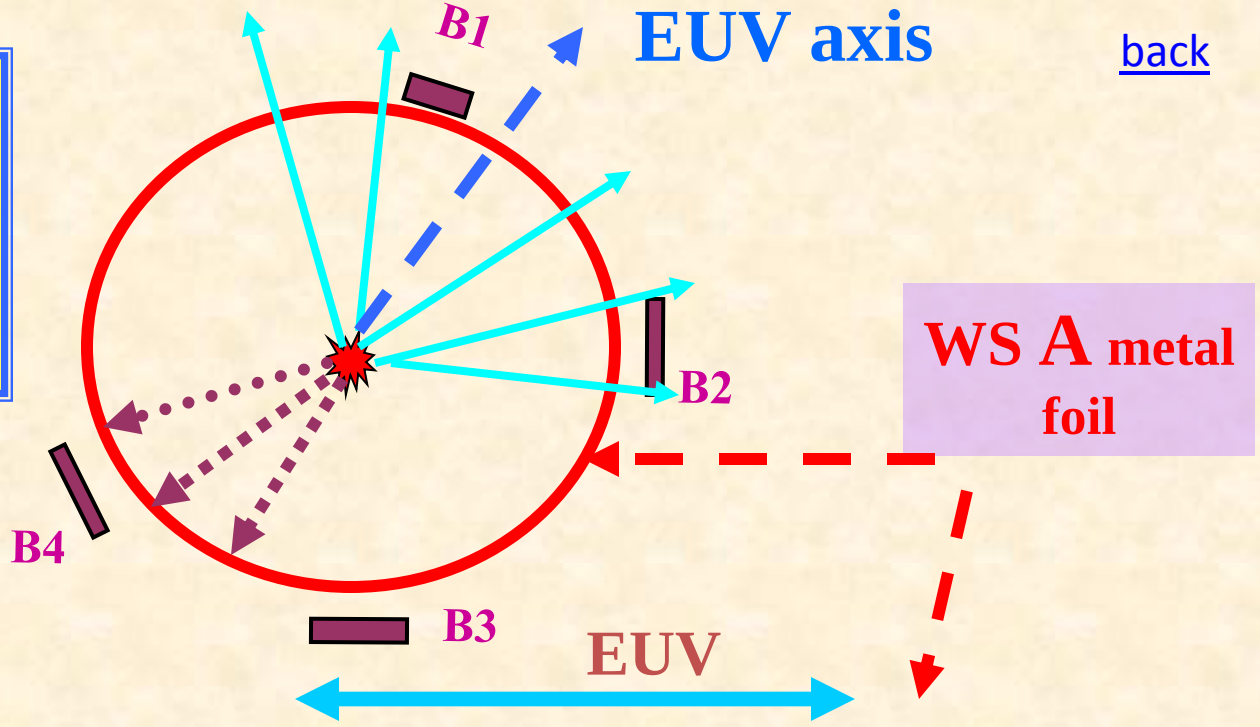
Jet electrodes geometry

Measurements of angular debris distributions: positions of samples.



Measurements of debris angular distributions: Witness Sample A – propagation of plasma; "Horizontal cross-section".

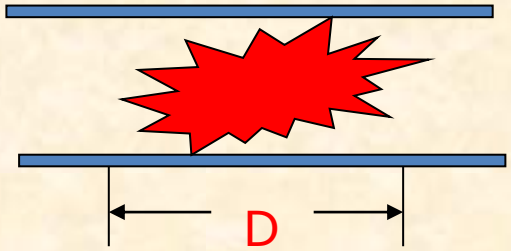
Electrode design allows to direct at least 90 % of expanding plasma opposite to EUV radiation





B3 B4 B1 B2 B3

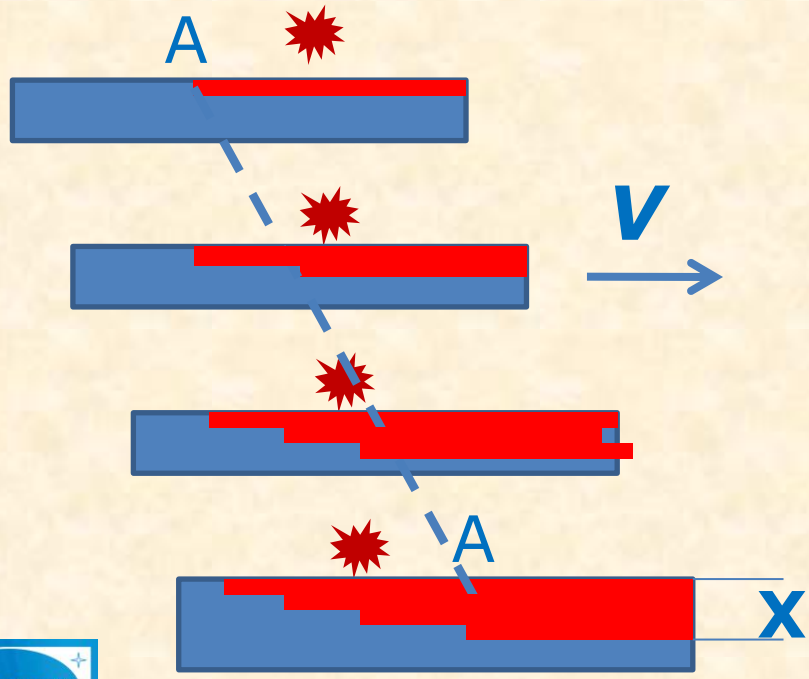
Possible heat load limitations



Power density dissipated on electrodes surface

$$PD = \tfrac{1}{2}\eta P_0 /(D^2)$$

Where
*D – size of single spot burning
•P_0 – full discharge power
• η - <1 ; takes into account dissipation without heating



Time of exposure of a point A on a surface of an electrode moving with velocity V

$$t_0 \approx D/V$$

Depth of heated layer :

$$x \approx (\chi t_0)^{1/2}$$

At given discharge power higher electrode speed means lower temperature of liquid tin.

$$P_0 \approx \frac{2}{\eta} * v^{1/2} * D^{3/2} * C * \Delta T$$

*Numerical modeling has been performed to calculate a dependence of a parameter D from the single shot energy. It was found to be about 0,5 - 1 cm.

*The parameter η describes geometry of the discharge gap as well processes of electrode "protection" due to surface tin evaporation. Numerical modeling yield that the parameter η also depends on the discharge energy and can be as high as 0,5 .

Assuming that allowed ΔT = 1000°C one can get an estimate of an expected heat limit :

$$P_o \approx 10\ V^{0,5}\ kW \quad (V \text{ in } cm/s)$$

For dissipation of 250 kW one needs V > 6 m/s

And for 500 kW V >= 25 m/s

Jet – Proto II (2011 – 2012); ASML – RnD ISAN

Principal Characteristics :

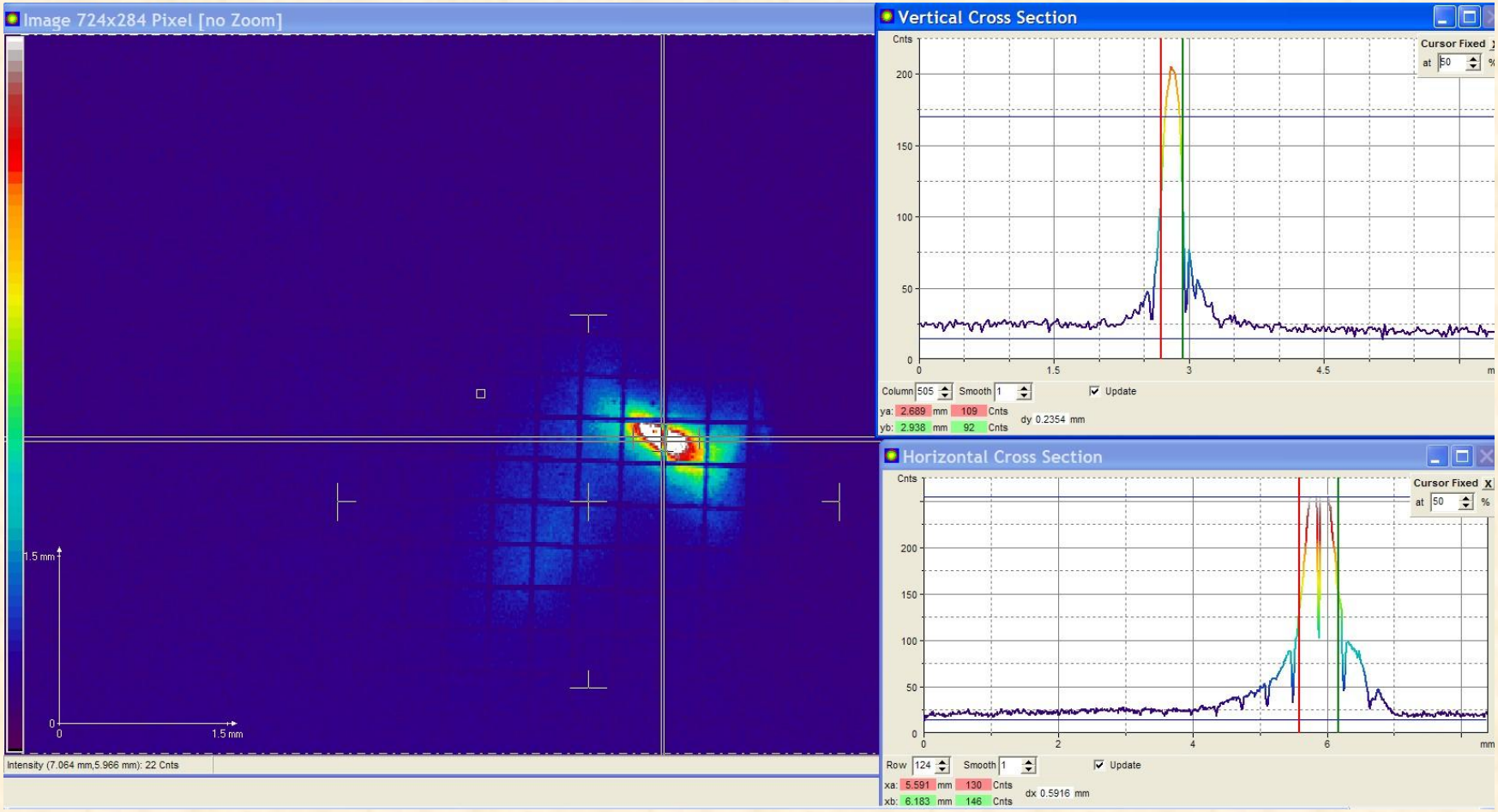
Capacitor - 0,4 uF
Inductance – 12 – 15 nH
Stored energy – up to 5 J

Cruise – 8 kHz x 4 J = 32 kW
With possibility of upgrading
- 16 kHz x 4 J = 64 kW

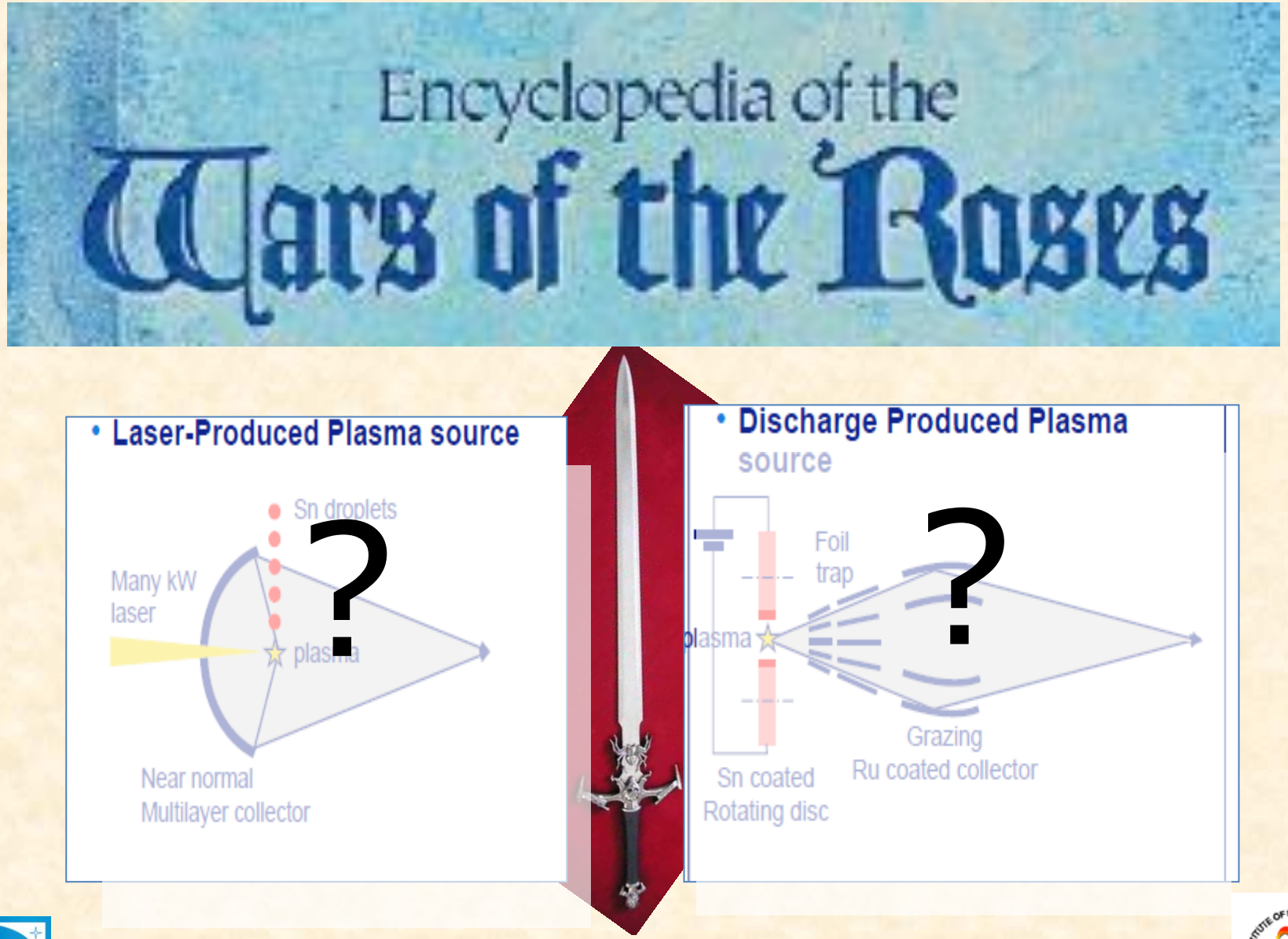
Jet material – Sn (8,5%) :
Working temperature (300 °C)

Jet velocity – 10 - 20 m/s -
CE = 2,5 – 3 %

Jet – Proto II - first experiments, E=3,6 J, Zr filter)



EUV source size - FWHM: 0,23мм x 0,59 мм
CE - 2,7 %


Encyclopedia of the
Wars of the Roses
• Laser-Produced Plasma source
Sn droplets
Many kW
laser
plasma
?
Near normal
Multilayer collector
• Discharge Produced Plasma
source
Foil
trap
plasma
?
Grazing
Ru coated collector
Sn coated
Rotating disc